DISKING AND MID- AND UNDERSTORY REMOVAL FOLLOWING AN ABOVE-AVERAGE ACORN CROP IN THREE MATURE OAK FORESTS IN SOUTHERN INDIANA

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Abstract.—We disked using small-scale equipment in the understory of three mature upland oak (*Quercus*) forests in southern Indiana immediately following acorn dispersal in an above-average seed crop year as a means of improving oak seedling establishment. Three different mid- and understory removal treatments were also applied to create favorable light conditions for the new cohort of oak seedlings. Disking increased the number of new oak seedlings by 14,586 per hectare. There were nearly 2¾ times more 2006 cohort oak seedlings in the disked areas than in nondisked areas. Both the injection and girdling mid- and understory removal treatments increased the estimated first-year seedling survival by 48 percent and 80 percent, respectively, over survival in the no treatment control. The basal bark treatment resulted in significantly fewer (63 percent) estimated surviving seedlings than the control treatment. Only two damage agents proved significant in reducing oak seedling numbers. Of 700 dead oak seedlings tallied at the end of the first growing season, 411 (59 percent) were killed by herbicide exposure resulting from volatilization of triclopyr in the basal bark treatment. An additional 135 (19 percent) seedlings were killed by pine voles. Deer browse and insect and disease damage proved inconsequential. Pine voles, which tunnel and feed on seedling roots and stems, are implicated in the majority of unaccounted-for oak seedling mortalities where the seedlings disappeared entirely.

INTRODUCTION

Acorn loss to predation and environmental extremes greatly reduces the number of acorns available for oak (*Quercus*) seedling establishment. Most viable acorns can be consumed by predators in years of low to moderate acorn production (Crow 1988). The impacts of white-tailed deer (*Odocoilus virginianus*) and rodent predation on oak seedling establishment are well documented (Steiner 1995, Ostfeld and others 1996). Soil scarification timed to coincide with end of acorn dispersal in the fall may reduce some loss of acorns to predation and environmental extremes and result in the establishment of substantially more oak seedlings on a site (Lhotka and Zaczek 2003).

Timely removal of shade-tolerant mid- and understory canopy layers prior to or following acorn dispersal is important to the establishment and survival of a cohort of oak seedlings. In undisturbed mature oak forests with well developed shade-tolerant mid- and understory canopy layers, more than 70 percent of planted oak seedlings died within 5 years of planting (Lorimer and others 1994). Loftis (1983) found that survival of a cohort of northern red oak (*Q. rubra* L.) seedlings in undisturbed oak forests in the southern Appalachians after 12 years was less than 10 percent. In order for new oak seedlings to develop into competitive oak advance reproduction, optimum understory light conditions must be obtained. Thinning from below to 60 to 70 percent of initial stand stocking, starting with the shade-tolerant mid- and understory may provide the optimum light levels required to establish competitive oak seedlings prior to overstory removal (Loftis 1990, Larsen and Johnson 1998).

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OBJECTIVES

The purpose of this study was to determine if oak seedling establishment from acorns was affected by scarification in combination with mid- and understory canopy removal. We tested the use of small-scale equipment to disk-scarify the soil to bury acorns while removing the shade-tolerant mid- and understory canopy layers in mature oak forests.

METHODS

The study was established in October 2005 in three 1.62-hectare blocks located in three different forest tracts (tracts I, N, and P) at the Southern Indiana Purdue Agricultural Center located in south-central Indiana. Each tract's overstory was dominated by mature oak, primarily white (*Q. alba* L.), northern red, and black oak (*Q. velutina* Lam.). Side-by-side paired transects were marked to facilitate efficient disking. Of each pair, one was designated to be disked and the other a nondisked control. These transects ranged from 46 m to 152 m in length and were spaced approximately 5 m to 9 m apart depending on block layout and topography.

Sound acorns were counted and identified to species using a 0.6 m x 0.6 m square sample frame at 9-m intervals along transects designated to be disked. Each acorn sample point was permanently marked. Soundness of acorns was determined using visual and tactile examination. Only fully mature acorns were counted as sound. Acorns with weevil exit holes, with caps still attached, with discolored cap attachment points, or which felt dried out or hollow when handled were not counted as sound. From Oct. 27 to Nov. 1, 2005, acorns were sampled in transects designated to be disked, but were not sampled in adjacent paired nondisked transects. In addition to acorns, advance oak reproduction established prior to fall 2005 was inventoried using the same sample plots.

Designated transects were disked on Nov. 1, 2005, using a 1.8-m wide double-row disk drawn by a 24-hp John Deere 855 4x4 diesel tractor with extra weight mounted to the front end. This size of tractor provided good maneuverability in forest settings with less than 10 percent slopes and required very minimal cutting of logs or understory trees. Disked transects were 1.8-m wide and disked to a depth of 7.6 to 15.2 cm.

Paired 1-m^2 sample plots were established and permanently marked at the same permanently marked acorn sampling plots. Paired sample plots were located within 1.5 m of each other, so that each was underneath the same tree crown, and so one was located in the disked transect and one in the paired nondisked transect. Oak seedlings were inventoried four times to track changes through the first growing season: May 25-31, July 17-24, August 23-31, and Oct. 12-18. Oak seedlings were tallied by species and by whether they were new germinants or older seedlings at each paired sample plot on each paired transect using a 1-m^2 sample frame. Dead seedlings were also tallied and cause of death, where identifiable, was noted. The corners of the sample frame were permanently marked so that the exact same plot location could be sampled each time.

Each 1.62-ha block was divided into four 0.41-ha plots and randomly assigned one of four different methods for controlling mid- and understory woody vegetation as means for ensuring adequate levels of light in the understory to sustain oak seedlings. The methods were 1) injection using an ax with a 4.4-cm bit and Pathway[2] herbicide delivered to injections using a backpack sprayer and gunjet nozzle; 2) chainsaw

[2]Garlon 4 and Pathway are registered tradenames of Dow AgroSciences.

girdle and felling with the application of Pathway to the girdle or cut stump; 3) low volume basal bark using the ester formulation of triclopyr (Garlon 4[2]) diluted to 20 percent concentration in a paraffinic petroleum distillate basal oil (AX-IT[3]); and 4) a no-removal control treatment. The objective of the mid- and understory removal was to remove the low shade component of the canopy while maintaining intact the high shade component. All mid- and understory trees greater than 1.27 cm diameter at breast height (d.b.h.) were treated, with the exception of a small number of oaks or occasional shade-tolerant trees growing in natural canopy gaps. These mid- and understory removal treatments were applied from June 29 to July 7, 2006. The efficacy of these treatments is not described here. However, their influence on oak seedling establishment was tested in this analysis.

A generalized linear model of the form:

$$y_i \sim \text{Overdispersed Poisson}\left(\mu_i e^{\mathbf{X}_i \boldsymbol{\beta}}, \omega\right)$$

was fit to the number of live seedlings surviving to October (y_i), 2006 in each sample plot *i*. This model is essentially an analysis of covariance (ANCOVA), except that errors are assumed to be Poisson, rather than normally, distributed. The Poisson model is more appropriate for count data. The predictors (X_i) included tree species (white oak, northern red oak, and black oak) as well as disking (nondisked versus disked), mid- and understory removal treatments (no-removal control, herbicide injection, girdling, and basal bark herbicide application) and tract (I, N, and P). The regression coefficient associated with each treatment combination (β) represents a multiplicative change in the probability that an acorn present in November will germinate and survive to the following October, relative to the survival rate for white oak in nondisked, no-removal control mid- and understory removal sub-plots (i.e. the intercept) (Gelman and Hill 2007). We accounted for differences in background acorn density among plots by entering the November 2005 acorn counts for each species as a covariate (μ_i). Acorn counts were extrapolated to acorns/m^2 and rounded to the nearest whole number to ease interpretation. Omega (ω) is a scale parameter, and does not affect the regression fit. In this hierarchical design, the experimental unit is the finest level of resolution for which the data were collected, in this case, the 1 m^2-sample plot. To account for problems associated with potential pseudoreplication, sample plot, transect line, and tract were initially included in the model as predictor variables to test for random effects. Random effects due to sample plot and transect line proved insignificant. However, there were differences between tracts and thus tract was kept as a predictor in the final model.

A full-factorial model was fit initially, including all possible interaction terms. Interaction terms were subsequently dropped if none of the associated regression coefficients were significant ($\alpha = 0.05$). Data were reported as observed seedling densities. Similar methods were used to analyze the number of mortalities due to herbicide exposure and rodent predation. Analyses were performed in R, version 2.5.1 (R Development Core Team 2007).

RESULTS AND DISCUSSION

Acorn Density and Distribution

Across all three tracts, the number of sound acorns in November 2005 for each of the three oak species was roughly proportional to the overstory basal areas for each species (Tables 1 and 2). Tract P had a disproportionately large number of white oak (WO) acorns compared to red oak (RO) and black oak (BO), whereas Tract I had a disproportionately large number of RO acorns compared to WO, with a very

[3]AX-IT is a registered trade name of Townsend Chemical.

Table 1.—Stand overstory basal area for three mature upland oak stands (I, N, and P) in southern Indiana receiving strip disking and mid- and understory removal treatments

	Tract			
Stand stocking	I	N	P	Mean
Overstory basal area		(m^2/ha)		
White oak	4	9	22	13
Red oak	10	6	2	7
Black oak	1	2	1	1
Total oak	15	17	25	21
Other species	17	7	4	10
Total overstory	32	24	29	31
Mid- and understory basal area	6	5	7	6
Total basal area	38	29	36	37

Table 2.—Observed numbers of acorns sampled shortly after dispersal in Nov. 2005 for three mature oak stands (I, N, and P) in southern Indiana receiving disking and mid- and understory removal treatments

	Tract			
Species	I	N	P	Mean
		(acorns/ha)		
White Oak	35,609	59,124	162,471	92,784
Red Oak	132,725	77,064	14,089	66,405
Black Oak	4,856	40,932	11,170	21,026
Total Oak	173,190	177,121	187,730	180,214
(n) 0.372 m^2 sample plots	133	213	212	558

minor component of BO. Tract N acorn numbers were more evenly distributed among the three species, RO accounting for a small majority of the total acorn count (44 percent). Total acorn numbers irrespective of species showed a fairly even distribution among the three tracts. An average across all three tracts of more than 180,000 acorns per hectare of all three species combined was estimated to be on the ground at the time of disking (Table 2). Lhotka and Zaczek (2003) reported 195,500 to 212,600 acorns per hectare on the ground in an oak-hickory stand in southern Illinois prior to soil scarification. Bundy and others (1991) reported 151,000 acorns on the ground in a mixed hardwood stand in southeastern Minnesota. Within tracts, acorn distribution was patchy, reflective of the patchy distribution of seed-bearing parent trees. More than 20 percent of the 558 0.372 m^2 sample plots contained no acorns, with more than 50 percent contained three or fewer acorns. More than 20 percent of sample plots contained 10 or more acorns, the equivalent of more than 270,000 acorns per hectare, with one sample plot containing 79 acorns. Steiner (1995) found that RO acorn numbers ranged from 1,300 to 490,518/ha with an average of 103,236/ha across four consecutive years and five widely separated stands in Pennsylvania. Because of the patchy distribution of acorns and uneven distribution between midstory removal treatment areas, sampled numbers of acorns were used as a covariate in the generalized linear model.

Oak Seedling Treatment Responses

Oak reproduction established before fall 2005 was scarce to nonexistent over much of each of the three tracts. Only 16 out of 558 pretreatment (0.372-m^2) sample plots had oak advance reproduction, which

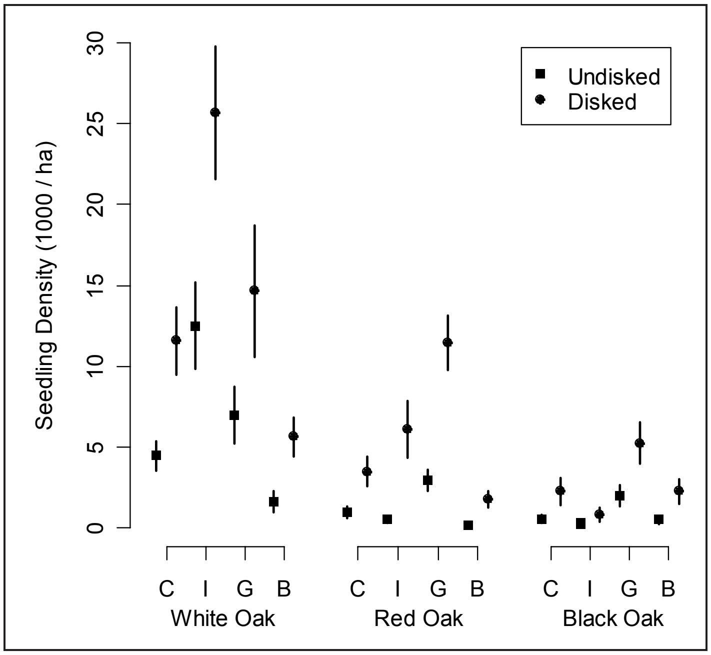

Figure 1.—Mean effects of disking and mid- and understory removal treatments on the density of a first-year cohort of oak seedlings growing in three mature oak stands in southern Indiana. Mid- and understory removal treatments were: no-removal treatment/control (C); herbicide injection (I); girdling and felling (G); and basal bark herbicide application (B).

may be extrapolated to 868 oak seedlings/ha. Post treatment, 6 out of 557 1-m^2 sample plots (143 oak seedlings/ha) in the disked areas had pre-fall 2005 oak advance reproduction, while 13 of 554 (326 oak seedlings/ha) nondisked sample plots did.

Overall, there were fewer RO and BO than WO 2006 cohort seedlings surviving to October 2006 (Table 3, Fig. 1). However, there were no differences in the rate of survival between the three species relative to the number of acorns occurring for each (Table 4). Significant tract differences also occurred. Tract P had 78 percent more oak seedlings/ha than tract N, which had 66 percent more than tract I (Table 3). Proportional differences in seedling densities among the three oak species also occurred between tracts, reflecting overstory basal area (Table 1) and acorn numbers (Table 2). Only one species by tract interaction proved significant. RO seedling density in tract P compared to the other two oak species in that tract was lower relative to RO seedling densities compared to the other oaks in the other tracts (Table 4). However, there were no differences between the species in their response to either disking or the midstory control treatments as indicated by a lack of significant interaction between these factors.

Disking significantly increased the likelihood that sound acorns on the ground in the fall resulted in live oak seedlings following the first growing season, compared to acorns falling in nondisked areas (Table 4). P-values in Table 4 less than 0.05 indicate significant treatment differences. Disking increased the number of new oak seedlings by 14,586 per hectare. There were nearly 2¾ times more 2006 cohort oak seedlings in the disked areas than in nondisked areas (Table 5). Other studies have found that soil scarification increases short-term oak seedling establishment relative to nonscarified controls. Scholz (1959) reported a 2.4-fold increase in RO seedlings in scarified plots versus nonscarified 2 years following treatment. Seven years following treatment, however, there were no differences in numbers of oak seedlings between scarified and nonscarified plots. Bundy and others (1991) reported no significant differences in RO seedling establishment between scarified and nonscarified treatment areas in a southeast Minnesota mixed hardwood forest. Lhotka and Zaczek (2003) found that scarification resulted in 5,100 oak seedlings per hectare versus 1,300 per hectare without scarification, a threefold increase, 1 year after treatment.

Table 3.—Observed density of 2006 cohort oak seedlings surviving to October 2006 for three mature oak stands (I, N, and P) in southern Indiana averaged across disking and mid- and understory removal treatments

	Tract			
Species	I	N	P	Mean
	(seedlings/ha)			
White Oak	603	1795	8942	4132
Red Oak	2534	1942	189	1439
Black Oak	77	1594	368	787
Total Oak	3214	5331	9499	6358
(n) 1-m^2 sample plots	262	442	407	1111

Table 4.-Estimated overdispersed Poisson regression coefficients for the effects of tree species, disking, understory treatment, and tract on oak seedling density (n = 3192, ω = 3.9, percent deviation explained = 29%)

		Estimate	SE	t	p-value
(Intercept)		-5.0832	0.5068	-10.03	<0.001
Species	Red Oak	0.0373	0.356	0.1	0.916
	Black Oak	-0.7958	0.9367	-0.85	0.396
Disking	Disked	1.9741	0.4201	4.7	<0.001
Understory	Injection	0.4438	0.1577	2.82	0.005
	Girdling	0.6545	0.1456	4.5	<0.001
	Basal Bark	-0.9797	0.2049	-4.78	<0.001
Tract	Tract N	1.7303	0.529	3.27	0.001
	Tract P	2.3414	0.5033	4.65	<0.001
Interactions	Red Oak : Tract N	-0.3937	0.4133	-0.95	0.341
	Black Oak : Tract N	0.5708	0.9637	0.59	0.554
	Red Oak : Tract P	-2.0319	0.5816	-3.49	<0.001
	Black Oak : Tract P	-0.0542	0.993	-0.05	0.956
	Disked : Tract N	-1.0421	0.4604	-2.26	0.024
	Disked : Tract P	-1.084	0.443	-2.45	0.014

Table 5.—Mean observed density of 2006 cohort oak seedlings surviving to October 2006 by disking treatment across three mature oak stands in southern Indiana. Different letters within columns indicate significant differences at α=0.05.

Disk treatment	WO	RO	BO	TOT
	---------------------------(seedlings/ha)---------------------------			
Disked	14093 a	5853 a	3034 a	22980 a
Not disked	6300 b	1245 b	848 b	8393 b

Table 6.—Estimated overdispersed Poisson regression coefficients for the effects of tree species, disking, and understory treatment on the number of seedlings killed by herbicide in their first year (n = 3192, ω = 0.53, percent deviation explained = 63%)

		Estimate	Std. Error	t	P-value
(Intercept)		-22.08	610.93	-0.04	0.971
Species	Red Oak	-18.39	490.24	-0.04	0.970
	Black Oak	-2.77	0.30	-9.27	<0.001
Disking	Disked	0.29	0.07	3.99	<0.001
Understory	Injection	16.61	610.93	0.03	0.978
	Girdling	0.04	797.55	0.00	1.000
	Basal Bark	19.66	610.93	0.03	0.974

Mid- and understory treatments removed between 15 percent and 19 percent of the total stand basal area in the three tracts. Both the injection and girdling mid- and understory removal treatments appeared to have a positive effect on first-year oak seedling survival (Table 4 and Fig. 1), increasing it by 48 percent and 80 percent, respectively, over survival in the no-removal control treatment. The basal bark treatment resulted in significantly fewer (63 percent) surviving seedlings than the control treatment (Fig. 1). A number of studies demonstrate that oak seedlings have poor survival in the low light conditions present in mature oak stands with shade-tolerant mid- and understories (Lorimer and others 1994, Crow 1988). Janzen and Hodges (1985) found that mid- and understory removal using injection and foliar herbicide applications in a mature southern bottomland oak stand increased numbers of new oak germinants by 100 percent 3 years after treatment. Loftis (1990) proposed methods for regenerating northern red oak in the southern Appalachians through thinning from below. In many stands much of the required basal area removal can be accomplished by removing the midstory and understory canopy layers. When these layers are removed while keeping much of the overstory intact, sufficient light reaches the forest floor to maintain oak seedling development. These light levels, however, are insufficient to maintain the growth and establishment of many of the oak seedlings' shade-intolerant competitors, such as yellow-poplar (*Liriodendron tulipifera* L.).

Oak Seedling Mortality

Mortality data represented only those dead seedlings that were actually observed and counted, and thus do not account for the number of seedlings that disappeared between sample dates. Two causes of mortality were readily observed: herbicide damage and pine vole (*Microtus pinetorum*) predation. Because of the relatively small number of herbicide-induced mortalities compared to the large number of sample plots, variability was too high to detect treatment differences in the model (Table 6). However, observationally, the effects were obvious, with quite complete oak seedling mortality occurring in concentrated areas of the basal bark treatment plots. Of the 700 dead oak seedlings tallied, 411 (59 percent) were killed by herbicide exposure. Herbicide-induced mortality occurred almost exclusively (96 percent) in the basal bark treatment. Although not well documented in the scientific literature, triclopyr herbicide in its ester formulation may volatilize at air temperatures exceeding 28 ˚C. Rathfon and Ruble (2006) showed reductions in Amur honeysuckle control when basal bark treatments using the ester formulation of triclopyr were applied at air temperatures reaching 33 ˚C. High temperatures on the dates of the basal bark treatment application in this study exceeded 28 ˚C. Volatilized triclopyr very likely injured oak seedlings, resulting in significantly fewer oak seedlings in the basal bark treatment compared to all other midstory

Table 7.—Estimated overdispersed Poisson regression coefficients for the effects of tree species, disking, understory treatment, and tract on the number of seedlings killed by pine voles in their first year (n = 3192, ω = 1.0, percent deviation explained = 15%)

		Estimate	SE	t	p-value
(Intercept)		-9.0794	1.0725	-8.47	<0.001
Species	Red Oak	1.925	1.0214	1.88	0.059
	Black Oak	1.1131	1.4155	0.79	0.432
Disking	Disked	1.4748	0.2263	6.52	<0.001
Understory	Injection	0.9595	0.3938	2.44	0.015
	Girdling	1.4487	0.3475	4.17	<0.001
	Basal Bark	0.9298	0.3899	2.38	0.017
Tract	Tract N	1.0509	1.0835	0.97	0.332
	Tract P	2.1426	1.0122	2.12	0.034
Interactions	Red Oak : Tract N	-0.885	1.1278	-0.78	0.433
	Black Oak : Tract N	0.0919	1.4979	0.06	0.951
	Red Oak : Tract P	-2.3771	1.1505	-2.07	0.039
	Black Oak : Tract P	-2.837	1.7379	-1.63	0.103

removal treatments (Fig. 1). However, early observations of seedling survival in the second growing season indicate that some oak seedlings tallied as dead due to herbicide exposure resprouted.

Pine vole activity was evident in all three tracts, primarily indicated by tunnels close to the soil surface and by exit holes. The majority of total mortality could not be identified with certainty because the seedlings disappeared altogether. Pine vole-induced mortality was observed when dead seedlings were easily pulled from the ground, revealing that the roots had been eaten off, or when dead seedling tops were found lying on the soil surface. This evidence was almost always found in combination with pine vole burrows on the sampled plot. Nineteen percent of tallied oak seedling mortality was due to pine vole predation. Seedling predation by species did not differ statistically (Table 7). Although there were 65 percent fewer RO seedlings than WO seedlings throughout all tracts and treatments, pine vole predation was not significantly different between the two species, indicating a disproportionate level of predation on RO seedlings versus WO seedlings. This result may indicate pine vole feeding preferences or it may only reflect closer proximity of RO versus WO seedlings to the pine voles. Seedlings in disked plots suffered increased levels of predation over their nondisked treatment counterparts (Table 7, Fig. 2). One possible explanation for this might be that the pine voles are attracted to the loosened soil in the disked areas because of easier tunneling. Pine vole tunneling, however, was observed in both disked and nondisked plots. Vole predation in the injection, girdling, and basal bark mid- and understory removal treatment plots were higher than in the control. Additionally, Tract P showed higher levels of vole predation than the other tracts. The increased numbers of oak seedlings that occurred in the disked plots compared to the nondisked plots, in the mid- and understory removal plots compared to their control, and finally in Tract P versus other tracts likely made these areas more attractive to foraging pine voles. Thus, pine voles appeared more attracted to, and predation on seedlings was higher in, areas where there were larger concentrations of oak seedlings, irrespective of particular treatments.

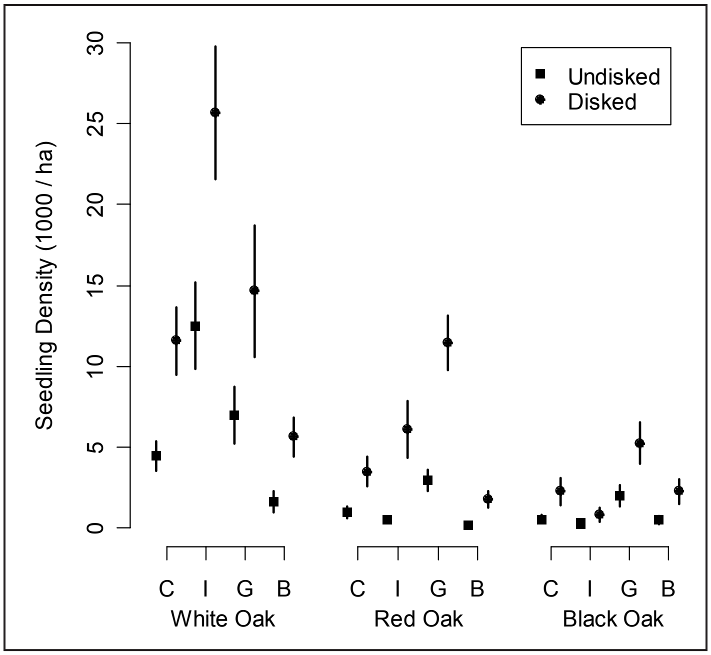

Figure 2.—Effects of disking and mid- and understory removal treatments on pine vole-induced mortality on a first-year cohort of oak seedlings growing in three mature oak stands in southern Indiana. Mid- and understory removal treatments were: no-removal treatment/ control (C); herbicide injection (I); girdling and felling (G); and basal bark herbicide application (B).

Deer browsing on this cohort of oak seedlings was almost nonexistent. No deer browse-induced mortality was observed in the first growing season. Thus, it is unlikely that the large number of missing seedlings unaccounted for in the mortality estimates were pulled from the ground or clipped off at ground level by deer. Insect and disease damage was likewise very rare to nonexistent. Pine vole predation may account for the majority of unexplained oak seedling mortality in the first growing season. Vole herbivory on oak stems, and roots was recognized as early as 1907 (Lantz 1907). Little research has been published since then on vole–oak interactions. Pine voles were attracted to the dense vegetation that resulted from timber harvests that removed a substantial portion of the overstory (Perry and Thill 2005). Ostfeld and Canham (1993) studied the role of voles in woody plant dynamics in early successional habitats. Neither of these studies examines vole–oak seedling dynamics in the oak seedling establishment phase under a mature oak forest canopy.

CONCLUSIONS

Disking immediately following acorn dispersal in the fall greatly increased oak seedling establishment one growing season later. Increasing ground-level light by mid- and understory removal improved first-year oak seedling survival. Timely removal of these canopy layers is important to first year oak seedling survival and critical to the development of new seedlings into competitive oak regeneration. When workers use the ester formulation of triclopyr for basal bark applications or any potentially volatile forms of herbicide in mid- and understory removal operations, they should time the treatment to avoid air temperatures exceeding 28 to 30 °C, thus preventing significant first-year oak seedling damage. Pine voles have never been implicated in first-year oak seedling mortality in previous oak regeneration studies. Our study shows that this seedling predator may have substantial localized effects on first-year oak seedling survival. More investigation is needed to determine the extent of pine voles' impact on oak regeneration dynamics, both spatially and temporally.

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